Tribology of solid-lubricated liquid carbon dioxide assisted machining

Citation for the original published paper (version of record):

Pusavec, F., Sterle, L., Kalin, M. et al (2020)
Tribology of solid-lubricated liquid carbon dioxide assisted machining
CIRP Annals - Manufacturing Technology, 69(1): 69-72
http://dx.doi.org/10.1016/j.cirp.2020.04.033

CIRP Annals - Manufacturing Technology 69 (2020) 69–72

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

Tribology of solid-lubricated liquid carbon dioxide assisted machining

Franci Pušavec[a,*], Luka Sterle[a], Mitjan Kalin[a], Dinesh Mallipeddi[b], Peter Krajnik (2)[b]

[a] *Faculty of Mechanical Engineering, University of Ljubljana, Ljubljana, Slovenia*
[b] *Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden*

ARTICLE INFO

Article history:
Available online 17 May 2020

Keywords:
Machining
Lubrication
Friction

ABSTRACT

An investigation is made into the lubrication capabilities of solid-lubricated liquid carbon dioxide (LCO_2) in comparison to flood lubrication, straight LCO_2 and oil-lubricated LCO_2 (MQL). The coefficient of friction is determined via tribological experiments, similar to machining, using an open tribometer which features an uncoated carbide insert sliding against a workpiece. Tribological experiments reveal superior performance of solid-lubricated LCO_2. The milling experiments as well indicate that solid-lubricated LCO_2 significantly reduces wear. The machined-surface topography is examined using high-magnification SEM, which shows no presence of adhered solid particles on the workpiece surface, providing a completely dry machining process.

1. Introduction

Sustainability is the main driver for replacing conventional metalworking fluids (MWFs) with cleaner solutions. Dry machining and Minimum-Quantity Lubrication (MQL) cannot fully substitute for flood cooling and lubrication in all machining operations due to poor heat-removal capabilities. Better cooling can be achieved with cryogenic machining utilizing liquid nitrogen (LN_2) and/or liquid carbon dioxide (LCO_2). However, their lubrication abilities are poor to nonexistent [1,2]. Therefore, cryogenic cooling is often combined with MQL. The latest developments in this field refer to a single-channel supply of pre-mixed LCO_2 and oil [3,4]. The efficiency of this technology depends on the solubility (polarity) of the oils used and the size and distribution of the generated oil droplets. Using solid lubricants mixed in different emulsions or oils has also proven to improve machinability via lower tool wear, lower cutting forces and better surface finish [5–7]. This can be attributed to a wider thermal operating range of solid particles, in comparison to oil-based lubricants [8], and lower friction [9]. However, no investigation has yet reported on combining liquid CO_2 cooling media with solid lubricants or supply of this mixture into a cutting zone via a single channel. The two most common solid lubricants, molybdenum disulphide (MoS_2) and graphite, are readily available in the form of fine powders. A common average particle size is in the range of 1–10 μm, which is comparable to the average droplet size in oil-lubricated LCO_2 [3]. Hence, a continuous supply of these powder particles into the stream of LCO_2 could facilitate a sustainable solid-lubricated LCO_2 solution. The micro-sized MoS_2 particles used here are a nontoxic alternative to (oil) additives. They cannot penetrate human cells and can be filtered. Not only is this alternative lubrication beneficial from both environmental and health perspectives, it also benefits by omitting subsequent cleaning process (using problematic cleaning agents).

Therefore, an attempt is made to understand the tribology of solid-lubricated LCO_2-assisted machining compared to flood lubrication, straight LCO_2 and oil-lubricated LCO_2. For this, a dedicated open tribometer is developed for measuring the coefficient of friction and contact temperature between the tool and the workpiece under conditions similar to machining. The validation of the proposed technology is further extended to real milling experiments to assess tool-wear. The surface-integrity aspects are addressed through (1) characterization of the local plastic deformation of the machined surface and (2) analysis of the surface topography by examining the achieved cleanliness of the process via possible adhesion of solid particles onto the workpiece.

2. Tribological experiments

In machining, the tribological conditions at the tool/workpiece and tool/chip interfaces are severe – high sliding speeds, temperatures exceeding 800 °C (1073 K) and contact pressures up to 3000 MPa – where friction causes several unwanted phenomena. Replicating such realistic conditions with conventional tribometers has proven challenging and several open tribometers have been developed to operate closer to the real tribological conditions in metal cutting [10,11]. These instruments apply high normal forces and run at high sliding speeds while exposing fresh workpiece surface at the contact, as is the case of machining. Moreover, realistic cooling and lubrication can be supplied into the contact zone, which affects both the temperature and the coefficient of friction.

The open tribometer developed for this study is mounted to a lathe and uses a cutting insert (Sumitomo SNMG120412N-EG) as the pin/cutting tool and a 42CrMo4 bar ($D = 70$ mm) as the workpiece. The pin is positioned perpendicular to the workpiece surface with an

---

[*] Corresponding author.
E-mail address: franci.pusavec@fs.uni-lj.si (F. Pušavec).

https://doi.org/10.1016/j.cirp.2020.04.033
0007-8506/

orthogonal tool clearance of $\alpha_0 = 0°$ and a rake angle of $\gamma_0 = 90°$. Just before the sliding contact, another insert of the same type is used to generate a freshly machined surface. In developing the tribometer, the first step was to calculate the normal force needed to achieve the required contact pressure. A finite-element (FE) simulation was used for this calculation, as the contact pressures exceed the elastic limit of the material. This causes plastic deformation and enlargement of the contact area, producing lower theoretical contact pressures when compared to Hertzian theory. Fig. 1 shows the distribution of contact stress between the pin and the workpiece at a normal force of F_N = 100 N. The pin was modelled as elastic (E_{pin} = 650 GPa, ν_{pin} = 0.31) and the workpiece as both elastic (E_{wp} = 210 GPa, ν_{wp} = 0.31) and plastic (σ_Y = 650 MPa, σ_{UTS} = 1000 MPa, ε_{UTS} = 0.12). The simulation yielded an elliptical pressure distribution, with a local maximum at 1503 MPa, which corresponds to machining [10].

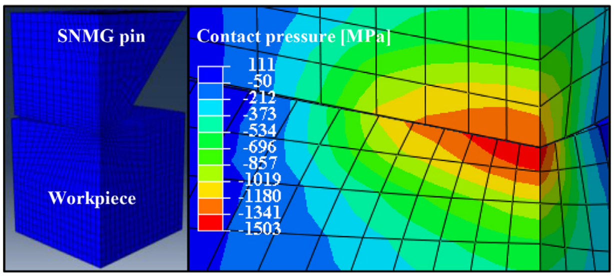

Fig. 1. FEM simulation of contact pressure (ABAQUS).

A detailed illustration of the tribometer used here is shown in Fig. 2. In addition to force measurements, a Type-K thermocouple (diameter 0.5 mm) is embedded in the pin/cutting insert. The distance between the outlet nozzle and the rake face is kept constant at 3 mm. The tool holder is mounted on a Kistler 9129AA dynamometer which is fixed on the linear guide rail of the lathe. A pneumatic actuator provides the predetermined normal force (F_N = 100 N). A constant feed of f = 1.3 mm/rev is used to omit interference between sliding marks. Argon is supplied between the cutting and sliding insert to prevent oxidation. The cutting tool moves with the same feed as the opposite pin/sliding insert and is positioned slightly in front of the pin (half the feed rate). As fresh surface material is continuously fed into the contact, the average coefficient of friction is expected to stay constant throughout the tests, whereas the temperature equilibrium depends on the particular cooling and lubrication used. Tribological tests include five different cooling-lubrication methods: (i) Dry; (ii) Emulsion (Blaser B-Cool 9665, 6%); (iii) straight LCO_2; (iv) oil-lubricated LCO_2; and (v) solid-lubricated LCO_2 – all at three different sliding speeds (100, 150 and 200 m/min). For the sake of repeatability, three repetitions of each condition are carried out. All cooling-lubricants are delivered at a similar pressure of 60 bar (6 MPa). LCO_2 and emulsion flow rates are measured using a Coriolis mass flow meter set at 200 g/min to provide sufficient cooling effect [3]. The oil-lubricated LCO_2 uses a special MQL oil (Rhenus Lub SSB, viscosity 3.5 mm^2/s at 20 °C) delivered through a single-channel system [3] with an oil flow rate of 100 g/hour (a typical MQL flow rate). Similarly, solid-lubricated LCO_2 uses pre-mixed LCO_2 and MoS_2 particles. Here a proprietary mixing mechanism (continuous, at 60 bar) is developed and used for the injection of solid particles into the stream of LCO_2.

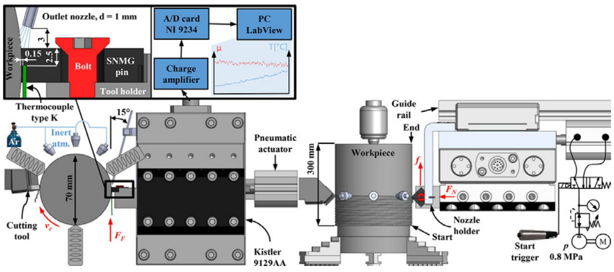

Fig. 2. Experimental setup for tribological experiments.

The flow rate of solid lubricant MoS_2 is 40 g/hour. Larger flow rates produce no further reduction in the coefficient of friction. The morphology of MoS_2 particles is characterized using a scanning electron microscope (SEM). Irregularly shaped particles are observed (Fig. 3 left), with a calculated average particle size of 5.6 μm (100 scanned particles).

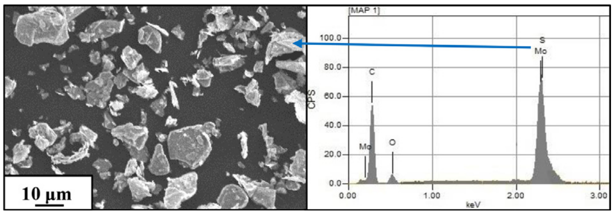

Fig. 3. SEM image of MoS2 particles and EDS mapping.

The results of the open tribometer tests are summarized in Fig. 4. Temperature equilibrium was achieved for all conditions tested except for dry and straight LCO_2, where linear temperature growth is observed from the minimum temperature at the start of the test to the maximum temperature at the end. Increasing the sliding speed results in a decrease in friction, also observed by other researchers [1,10,11]. Higher sliding speeds lead to higher temperatures, which facilitate thermal softening leading to a reduction in the coefficient of friction [5]. In contrast to oil, the straight LCO_2 showed no lubrication effect, only contact cooling.

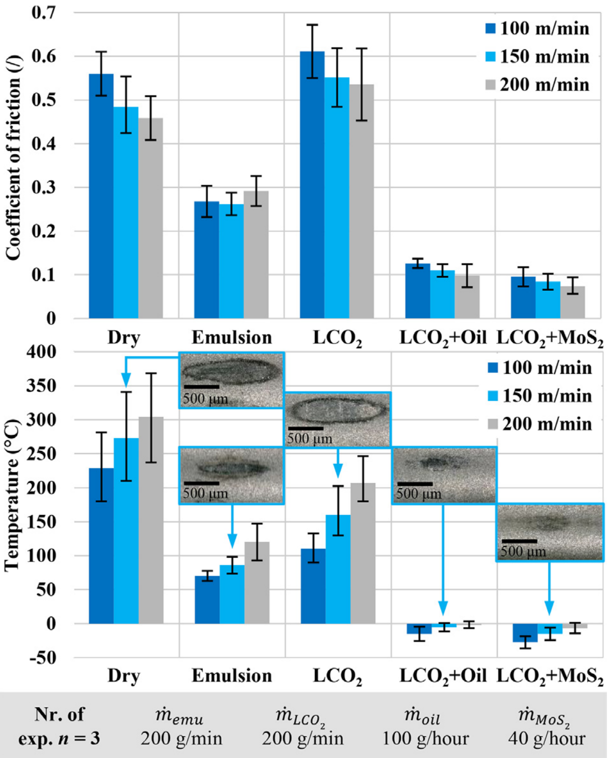

Fig. 4. Tribological results: (a) Coefficient of friction; (b) Temperature.

The feasibility of using (nano-engineered) MoS_2 with water-based emulsion or MQL was demonstrated in [12]; these layered particles were able to penetrate into the contact surfaces and are less sensitive to high temperature when compared to organic molecules used in oils. The lowering of the coefficient of friction at sufficient contact pressure is attributed to the breaking of particles into thin flakes, which under pressure stick to the surface, forming a tribofilm. This type of tribological mechanism leads to improved lubrication and a lowering of friction. In this study, MoS_2 microparticles are used, which offer similar properties at a much lower price.

Fig. 4 shows the measured coefficient of friction and pin wear at 150 m/min sliding speed. The highest pin wear, due to lack of lubrication, is observed for dry and straight LCO_2. Compared to dry machining, the use of emulsion reduces the coefficient of friction by approximately 50% (from 0.56 to 0.27 at 100 m/min). Considering the friction and temperature results, the lower temperature and pin wear can be attributed to combined cooling and lubrication effects.

Combining LCO_2 with oil reduces the coefficient of friction by approximately 80% (0.61 to 0.13 at lowest speed and 0.54 to 0.1 at highest speed). Similar trends were observed by [10] for the same workpiece material with a TiN-coated WC—Co pin, where oil-lubricated MQL was compared to dry conditions. This is corroborated by the lower temperatures measured in the sliding zone. As less heat is generated with solid lubricated LCO_2 (while the cooling capability of LCO_2 stays unchanged), lower temperatures ranging from −15 to −2 °C are achieved. Thus, reducing friction during machining lowers the total generated heat (frictional and material separation work), resulting in lower tool temperatures with the same LCO_2 cooling capability.

The adhered solid lubricant at the sliding surface is critical in the formation of a tribofilm [8]. However, in the case of solid-lubricated LCO_2, it is suspected that the formation of the tribofilm in the contact zone is responsible for the reduction of the observed coefficient of friction values – 0.09 at the lowest sliding speed and 0.07 at the highest. This represents a roughly 30% decrease compared to oil-lubricated LCO_2. Moreover, a temperature drop of 10 °C was observed with solid lubricants in comparison to oil-lubricated LCO_2. From the measurement results, it has been observed also that when contact between the tool and workpiece is established, the average coefficient of friction stays constant throughout the experiment. This implies that a constant supply of MoS_2 powder actively sustains the formation of the tribofilm. The microscopic analysis of the pins reveals negligible wear, with only a thin layer of MoS_2 particles adhered to the surface of the pin. The results shown here demonstrate a superior reduction of friction coefficient in the solid-lubricated LCO_2 compared to all tested cooling-lubrication methods, including the oil-lubricated LCO_2.

3. Milling experiments

In addition to the tribological experiments, the solid-lubricated LCO_2 technology is tested in a real machining application to compare oil-lubricated LCO_2 with emulsion flooded machining. The dry and straight LCO_2 conditions used in the tribological experiments are not considered here due to the poor lubrication properties observed. Machining experiments are performed on a Heller H 2000 horizontal machining centre equipped with through-spindle delivery of LCO_2 via a 1-mm inner-diameter capillary tube that feeds lubricated LCO_2 to the milling tool. When emulsion is selected, it flows in a spindle tube around the LCO_2 capillary tube, as is standard. The mass flow rates used for flood machining and LCO_2 with oil and MoS_2 are the same as in the tribological experiments. Delivery of the coolant is achieved through the milling cutter via a central channel (diameter $d = 1$ mm), which splits into four outlet nozzles ($d = 0.5$ mm) for each cutting edge. Nozzles are positioned 10 mm above the tool face, as shown in Fig. 5. The inner channel and the four outlet nozzles are customized (using EDM) for a flat end mill ($d = 12$ mm, $z = 4$). The workpiece material (42CrMo4 steel) is milled with the following parameters: $v_C = 150$ m/min, $f_z = 0.05$ mm, $a_p = 10$ mm, $a_e = 3$ mm. A critical tool flank wear of $VB = 0.3$ mm is achieved in 36 min when using emulsion. Thus, the comparison of tool wear for oil- and solid-lubricated LCO_2 is made in the same machining time, with everything repeated twice. In the case of oil-lubricated LCO_2, flank wear reached $VB = 0.25$ mm with a wear width along the edge of 2.1 mm. Similar tool-wear evolution has been reported when milling with oil-lubricated LCO_2 in comparison to emulsion [4, 13-14]. Note that the best machining results are observed with solid-lubricated LCO_2, with a further reduction of tool wear to $VB = 0.21$ mm and wear width along the edge of 1.8 mm (Fig. 5). This can be attributed to the ability of solid lubricants to form a tribofilm with better lubrication effect.

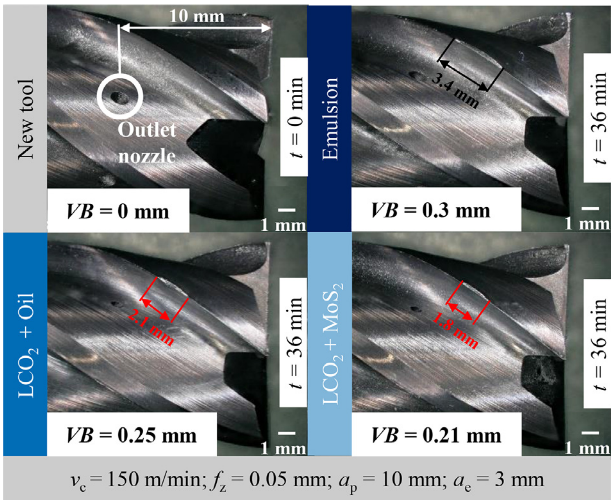

Fig. 5. Tool wear comparison for cooling and lubricating techniques.

At the beginning of tool-life tests, when cutting tools were new, sample surfaces were analysed. Samples are cleaned with isopropyl alcohol (IPA) in an ultrasonic bath and examined in an SEM (LEO Gemini 1550 equipped with a field emission gun; imaging performed at an acceleration voltage of 5 kV). Micrographs showing the topography of milled surfaces, along with measured surface-area roughness values (S_z, S_a and S_q), are given in Fig. 6. The microscopy reveal no solid particles on the machined surface. This indicates that the ultrasonic-bath cleaning removed all MoS_2 particles from the machined surface and that MoS_2 particles are not deeply embedded in the sample. Therefore, the results presented here indicate that solid lubrication is advantageous over MQL with oils, where surface degreasing after machining is required for cleaning.

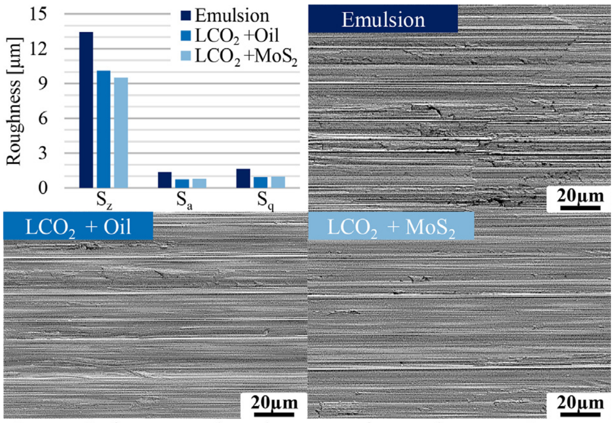

Fig. 6. Surface topography and average surface roughness area S_A.

Machined surface-area roughness values are measured using Alicona Infinite Focus SL (area: 8 mm x 8 mm). Oil- and solid-lubricated LCO_2 yield similar surface texture. On average, the use of emulsion increases S_z by 76%, S_a by 32% and S_q by 72% when compared to the lubricated LCO_2 methods. The reduction of the coefficient of friction plays an important role in surface finish as tool-workpiece adhesion and flank-face rubbing should be minimized when seeking to achieve best surface finish.

The observed smearing marks, material depositions and surface cracks on the topography appear to be the lowest in the case of solid lubricated machining. This is in line with the observations from tribological experiments.

4. Conclusions

A novel solid-lubricated LCO_2 technology is developed and evaluated experimentally. This technology demonstrates the feasibility of using solid lubricants mixed with LCO_2 for superior machining. The technology is verified via tribological and milling experiments utilizing a single-channel, through-tool delivery of solid-lubricated LCO_2. Specific findings are:

- Solid-lubricated LCO_2 achieves the lowest values of coefficient of friction and wear in tribological testing and even outperforms the oil-lubricated LCO_2.
- In comparison to emulsion, the coefficient of friction between the cutting tool and workpiece is reduced from 0.25 to 0.1 in oil-lubricated LCO_2; in the case of solid-lubricated LCO_2 a further decrease to 0.09 (64% reduction).
- The MoS_2 solid particles, used with LCO_2, show the capability of tribofilm formation in the contact zone. The tribofilm is sustained throughout the experiments as the coefficient of friction remains constant during sliding tests.
- The observations in tribological experiments are further confirmed in milling experiments. After 36 min of machining, oil-lubricated LCO_2 result in 16% lower wear than flood machining. In the case of solid-lubricated LCO_2, the wear is even smaller – 30% lower compared to emulsion.
- Machining with solid-lubricated LCO_2 results in a dry machining process without the need for excessive cleaning and/or degreasing of the machined surfaces.

Acknowledgments

Special thanks to ARRS (Slovenian Research Agency) for the funding of this research through projects (L2-8184 and P2-0266). The support of Chalmers Centre for Metal Cutting Research (MCR) is also acknowledged.

References

[1] Courbon C, Pušavec F, Dumont F, Rech J, Kopač J (2013) Tribological Behavior of Ti6Al4V and Inconel 718 Under Dry and Cryogenic Conditions – Application to the Context of Machining with Carbide Tools. *Tribology International* 66:72–82.

[2] Jawahir I-S, Attia H, Biermann D, Duflou J, Klocke F, Meyer D, Newman S-T, Pušavec F, Putz M, Rech J, Schulze V, Umbrello D (2016) Cryogenic Manufacturing Processes. *Annals of the CIRP* 65(2):713–736.

[3] Grguraš D, Sterle L, Krajnik P, Pušavec F (2019) A Novel Cryogenic Machining Concept Based on a Lubricated Liquid Carbon Dioxide. *International Journal of Machine Tools and Manufacture* 145:103456.

[4] Wika K-K, Litwa P, Hitchens C (2019) Impact of Supercritical Carbon Dioxide Cooling With Minimum Quantity Lubrication on Tool Wear and Surface Integrity in the Milling of AISI 304L Stainless Steel. *Wear* 426-427/B:1691–1701.

[5] Reddy NS-K, Nouari M, Yang M (2010) Development of Electrostatic Solid Lubrication System for Improvement in Machining Process Performance. *International Journal of Machine Tools and Manufacture* 50:789–797.

[6] Rao D-N, Krishna P-V (2008) The Influence of Solid Lubricant Particle Size on Machining Parameters in Turning. *International Journal of Machine Tools and Manufacture* 48:107–111.

[7] Nam J-S, Lee P-H, Lee S-W (2011) Experimental Characterization of Micro-drilling Process Using Nanofluid Minimum Quantity Lubrication. *International Journal of Machine Tools and Manufacture* 51:649–652.

[8] Stachowiak G-W, Batchelor A-W (2005) *Engineering Tribology*, 3rd ed. Butterworth-HeinemannUK.

[9] Sterle L, Kalin M, Pušavec F (2018) Performance Evaluation of Solid Lubricants Under Machining-Like Conditions. *Procedia CIRP* 77:401–404.

[10] Rech J, Arrazola P-J, Claudin C, Courbon C, Pušavec F, Kopač J (2013) Characterisation of Friction and Heat Partition Coefficients at the Tool-work Material Interface in Cutting. *Annals of the CIRP* 62:79–82.

[11] Bonnet C, Valiorgue F, Rech J, Claudin C, Hamdi H, Bergheau J-M, Gilles P (2008) Identification of a Friction Model Application to the Context of Dry Cutting of an AISI 316l Austenitic Stainless Steel With a TiN Coated Carbide Tool. *International Journal of Machine Tools and Manufacture* 48:1211–1223.

[12] Krajnik P, Rashid A, Pušavec F, Remškar M, Yui A, Nikkam N, Toprak M-S (2016) Transition to Sustainable Production – Part III: Developments and Possibilities for Integration of Nanotechnology into Material Processing Technologies. *Journal of Cleaner Production* 112:1156–1164.

[13] Bergs T, Pušavec F, Koch M, Grguraš D, Doebbler B, Klocke F (2019) Investigation of the Solubility of Liquid CO_2 and Liquid Oil to Realize an Internal Single Channel Supply in Milling of Ti6Al4V. *Procedia Manufacturing* 33:200–207.

[14] Hanenkamp N, Amon S, Gross D (2018) Hybrid Supply System for Conventional and CO_2/MQL-based Cryogenic Cooling. *Procedia CIRP* 77:219–222.